USE OF COAL DRYING TO REDUCE WATER CONSUMED IN PULVERIZED COAL POWER PLANTS

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by

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ABSTRACT

This is the second Quarterly Report for this project. The background and technical justification for the project are described, including potential benefits of reducing fuel moisture, prior to firing in a pulverized coal boiler. A description is given of the equipment, instrumentation and procedures being used for the fluidized bed drying experiments. Results of drying tests performed with North Dakota lignite, having a 6.35 mm (¼") top size, are presented. The experiments were performed with a 381 mm (15") settled bed depth, with inlet air and in-bed heater surface temperatures ranging from 43 to 66°C, with superficial air velocity ranging from 0.2 m/s to 1.65 m/s, and with rate of heat transfer from the in-bed tube bundle to the lignite varying from 0 to 140 $\frac{W}{\text{kg wet coal}}$.

Drying rate is shown to be a strong function of air velocity, drying temperature and rate of in-bed heat transfer.

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INTRODUCTION

Background

Low rank fuels such as subbituminous coals and lignites contain significant amounts of moisture compared to higher rank coals. Typically, the moisture content of subbituminous coals ranges from 15 to 30 percent, while that for lignites is between 25 and 40 percent.

High fuel moisture has several adverse impacts on the operation of a pulverized coal generating unit. High fuel moisture results in fuel handling problems, and it affects heat rate, mass rate (tonnage) of emissions, and the consumption of water needed for evaporative cooling.

This project deals with lignite and subbituminous coal-fired pulverized coal power plants, which are cooled by evaporative cooling towers. In particular, the project involves use of power plant waste heat to partially dry the coal before it is fed to the pulverizers. Done in a proper way, coal drying will reduce cooling tower makeup water requirements and also provide heat rate and emissions benefits.

The technology addressed in this project makes use of the hot circulating cooling water leaving the condenser to heat the air used for drying the coal (Figure 1). The temperature of the circulating water leaving the condenser is usually about 49°C (120°F), and this can be used to produce an air stream at approximately 43°C (110°F). Figure 2 shows a variation of this approach, in which coal drying would be accomplished by both warm air, passing through the dryer, and a flow of hot circulating cooling water, passing through a heat exchanger located in the dryer.

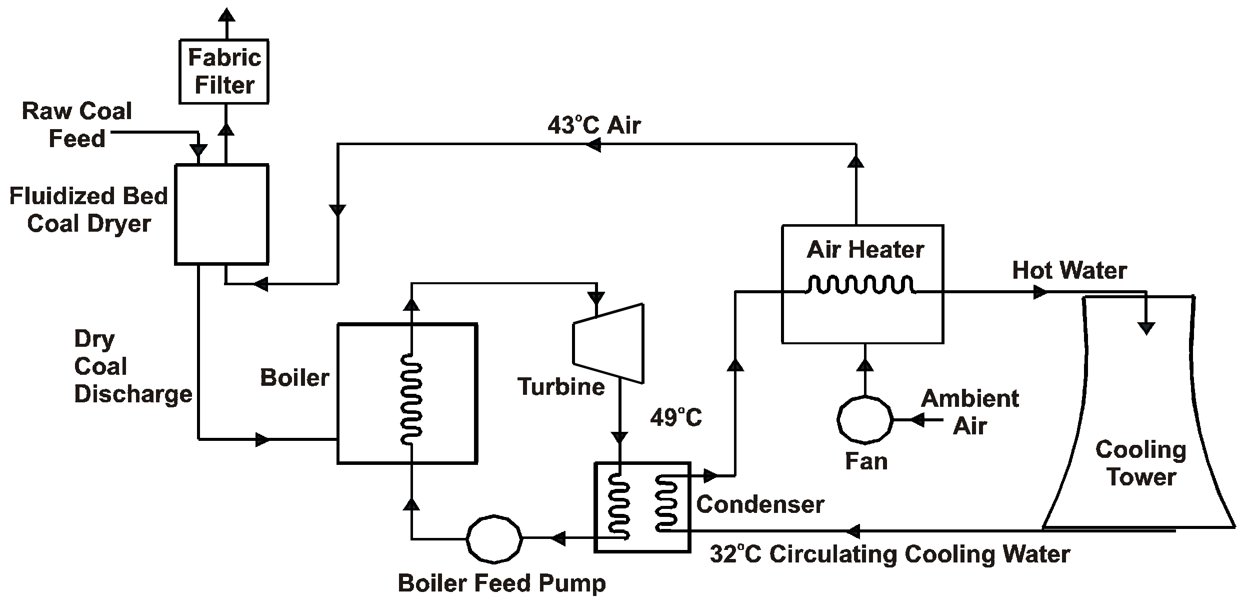

Figure 1: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 1)

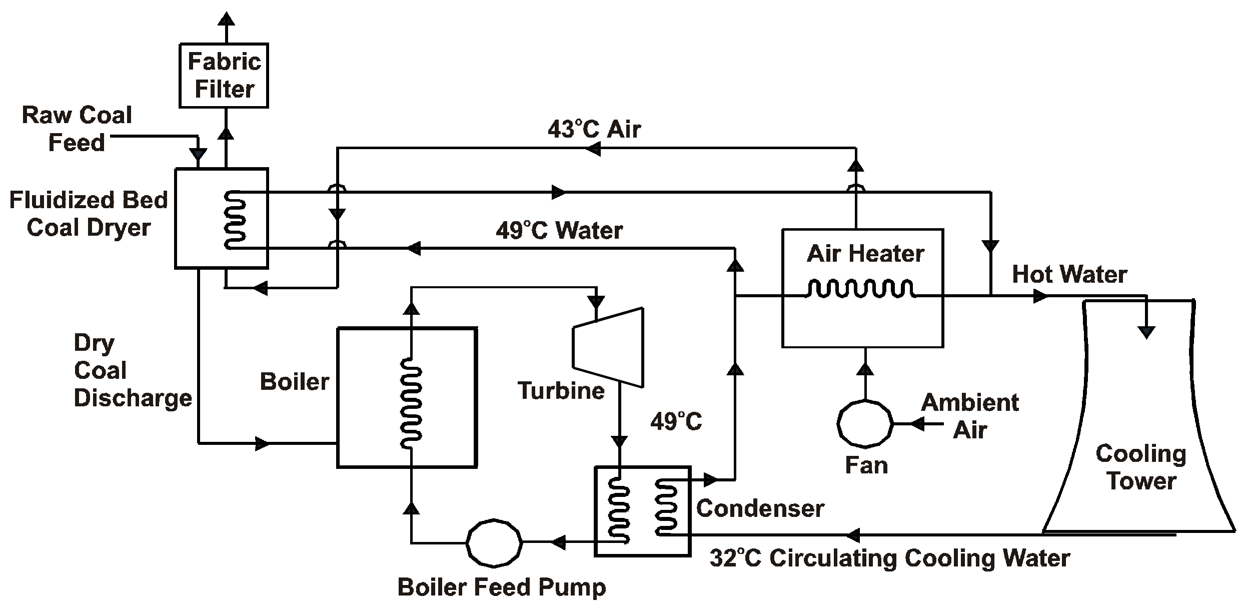

Figure 2: Schematic of Plant Layout, Showing Air Heater and Coal Dryer (Version 2)

Previous Work

Two of the investigators (Levy and Sarunac) have been involved in work with the Great River Energy Corporation on a study of low temperature drying at the Coal Creek Generating Station in Underwood, North Dakota. Coal Creek has two units with total gross generation exceeding 1,100 MW. The units fire a lignite fuel containing approximately 40 percent moisture and 12 percent ash. Both units at Coal Creek are equipped with low NO_x firing systems and have wet scrubbers and evaporative cooling towers.

The project team performed a theoretical analysis to estimate the impact on cooling water makeup flow of using hot circulating water to the cooling tower to heat the drying air and to estimate the magnitude of heat rate improvement that could be achieved at Coal Creek Station by removing a portion of the fuel moisture. The results show that drying the coal from 40 to 25 percent moisture will result in reductions in makeup water flow rate from 5 to 7 percent, depending on ambient conditions (Figure 3). For a 550 MW unit, the water savings are predicted to range from 1.17×10^6 liters/day (0.3×10^6 gallons/day) to 4.28×10^6 liters/day (1.1×10^6 gallons/day). The analysis also shows the heat rate and the CO_2 and SO_2 mass emissions will all be reduced by about 5 percent (Ref. 1).

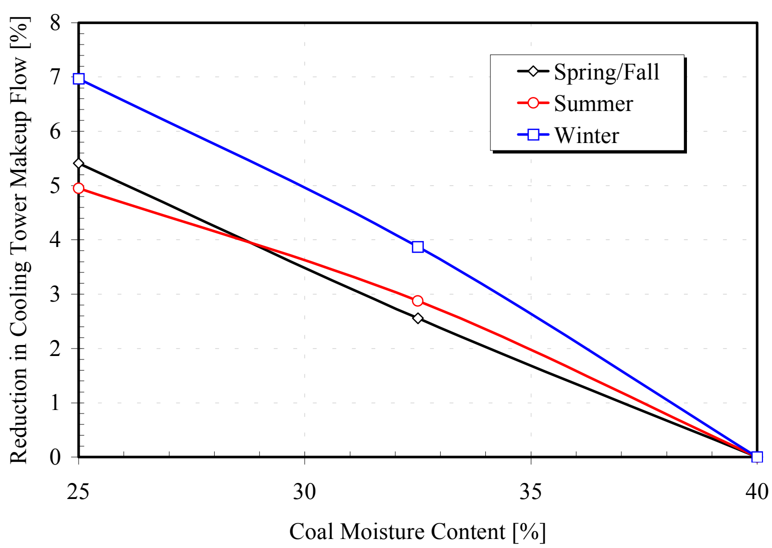

Figure 3: The Effects of Coal Moisture on Cooling Tower Makeup Water

A coal test burn was conducted at Coal Creek Unit 2 in October 2001 to determine the effect on unit operations. The lignite was dried for this test by an outdoor stockpile coal drying system. On average, the coal moisture was reduced by 6.1 percent, from 37.5 to 31.4 percent. Analysis of boiler efficiency and net unit heat rate showed that with coal drying, the improvement in boiler efficiency was approximately 2.6 percent, and the improvement in net unit heat rate was 2.7 to 2.8 percent. These results are in close agreement with theoretical predictions (Figure 4). The test data also showed the fuel flow rate was reduced by 10.8 percent and the flue gas flow rate was reduced by 4 percent. The combination of lower coal flow rate and better grindability combined to reduce mill power consumption by approximately 17 percent. Fan power was reduced by 3.8 percent due to lower air and flue gas flow rates. The average reduction in total auxiliary power was approximately 3.8 percent (Ref. 1).

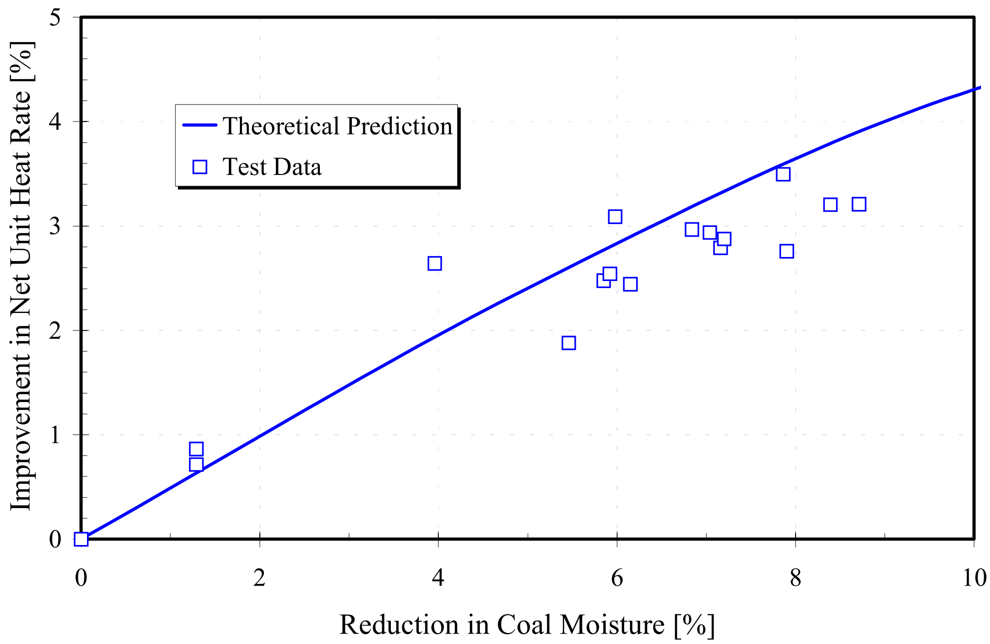

Figure 4: Improvement in Net Unit Heat Rate Versus Reduction in Coal Moisture Content

This Investigation

Theoretical analyses and coal test burns performed at a lignite fired power plant show that by reducing the fuel moisture, it is indeed possible to improve boiler performance and unit heat rate, reduce emissions and reduce water consumption by the evaporative cooling tower. The economic viability of the approach and the actual impact of the drying system on water consumption, unit heat rate and stack emissions will depend critically on the design and operating conditions of the drying system.

The present project is evaluating two alternatives (fluidized and fixed bed dryer designs) for the low temperature drying of lignite and Power River Basin (PRB) coal. Drying studies are being performed to gather data and develop models on drying kinetics. In addition, analyses are being carried out to determine the relative costs and performance impacts (in terms of heat rate, cooling tower water consumption and emissions) of these two drying options, along with the development of an optimized system design and recommended operating conditions.

The project is being carried out in five tasks:

Task 1: Fabricate and Instrument Equipment

Laboratory scale fixed bed and fluidized bed drying systems will be designed, fabricated and instrumented in this task.

Task 2: Perform Drying Experiments

The experiments will be carried out with both lignite and PRB coals, while varying superficial air velocity, inlet air temperature and specific humidity. In the fluid bed experiments, batch bed experiments will be run with different particle size distributions. The fixed bed experiments will include a range of coal top sizes. Bed depths will be varied for both the fixed and fluidized bed tests.

Task 3: Develop Drying Models and Compare to Experimental Data

In this task, the laboratory drying data will be compared to equilibrium and kinetic models to develop models suitable for evaluating tradeoffs between dryer designs.

Task 4: Drying System Design

Using the kinetic data and models from Tasks 2 and 3, both fluidized bed and packed bed dryers will be designed for 600 MW lignite and PRB coal-fired power plants. Designs will be developed to dry the coal by various amounts. Auxiliary equipment such as fans, water to air heat exchangers, dust collection system and coal crushers will be sized, and installed capital costs and operating costs will be estimated.

Task 5: Analysis of Impacts on Unit Performance and Cost of Energy

Analyses will be performed to estimate the effects of dryer operation on cooling tower makeup water, unit heat rate, auxiliary power, and stack emissions. The cost of energy will be estimated as a function of the reduction in coal moisture content. Cost comparisons will be made between dryer operating conditions (for example, coal particle feed size to fluidized beds and superficial air velocity for both fluidized bed and fixed bed dryers) and between dryer type.

The project was initiated on December 26, 2002. The project schedule is shown in Figure 5.

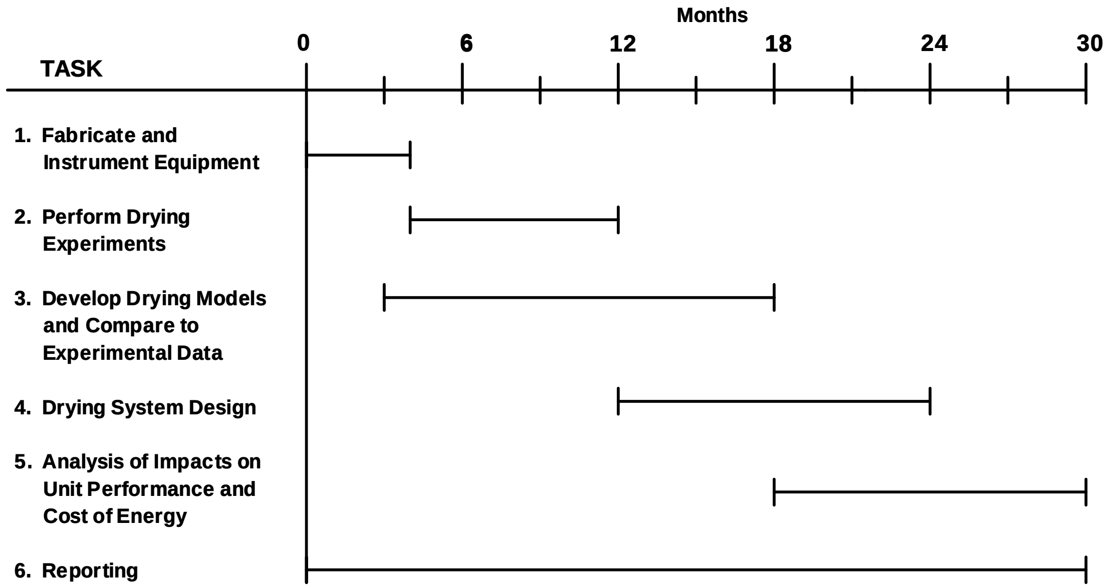

Figure 5: Project Schedule

EXPERIMENTAL

Test Apparatus

The drying experiments are being performed in the Energy Research Center's Fluidized Bed Laboratory. The bed vessel is 152.4 mm (6") in diameter, with a 1372 mm (54") column and a sintered powder metal distributor plate. The air and entrained coal particles pass through a filter bag before the air is discharged from the apparatus (Figure 6). Compressed air used in the experiments flows though a rotameter and an air heater before entering the plenum. Operating at 1.6 m/s of superficial air velocity in the 152.4 mm (6-inch) diameter bed, the electrically heated, air heater can attain a maximum steady state temperature of 66°C (150°F).

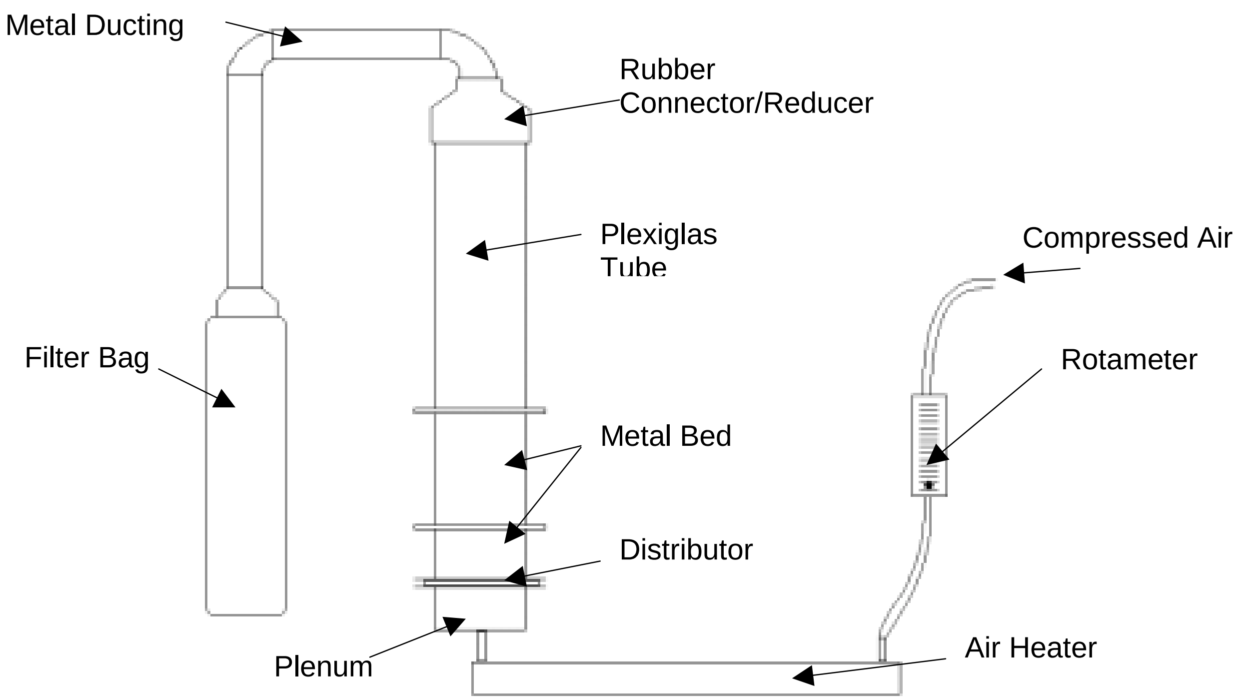

Figure 6: Sketch of Experimental Bed Setup

Thermocouples inserted through the bed wall are used to measure vertical distribution of bed temperature. A horizontal bundle of eighteen 469.9 mm (½”) diameter electric heating elements is used to provide in-bed heating. The heaters are located in the region from 51 mm (2”) to 304.8 mm (12”) above the distributor and are instrumented with thermocouples to indicate heater surface temperature. By controlling power to the heaters, the heater surface temperature can be operated in a range from 38°C (100°) to 65.6°C (150°F). At a given heater surface temperature, total heat flux to the bed can be reduced from the maximum by disconnecting selected heaters from the power supply.

Test Procedure

Batch bed drying tests were performed to determine the effect of superficial air velocity, inlet air and heater surface temperatures, and rate of heat transfer from the in-bed tube bundle to the coal on rate of drying. These tests were performed with a packed bed depth of 381 mm (15"), and with specific humidity of the inlet air ranging from 0.002 to 0.008. Small samples of the coal were removed from the bed during the drying tests and coal moisture was measured. This was determined by drying samples of the coal in crucibles in an oven at 110°C for 5 to 6 hours, and weighing the samples before and after drying. The complete test procedure used in these experiments is described in Table 1.

Table 1

Procedure for Drying Tests

1. With no coal in bed, turn on compressor, set air flow to desired value, turn on air preheater and allow system to reach steady-state at desired temperature. Measure inlet relative humidity and dry bulb temperature of air.
2. Once air is at steady-state, turn off air preheater and air flow, load coal into bed, turn on all heaters and air flow to appropriate values, start stopwatch, and record pressure of inlet air from pressure gauge above rotameter.
3. Begin recording temperatures after 5 minutes, collect small samples of lignite from bed, measure wet and dry bulb temperatures at exit of bed, record values for temperature readings at each assigned thermocouple, adjust voltage regulators for the heaters so that surface temperatures remain steady at appropriate values, and repeat this procedure for each time interval on data sheet.
4. At end of test, shut off heaters but keep air flow on to cool the heaters, detach filter bag, load coal samples into crucibles, place crucibles into oven, set to 100°C, and leave for 5-6 hours or overnight, remove remaining lignite from the bed and weigh it.
5. Analyze results.

Results and Discussion

The experiments performed in this reporting period were carried out with North Dakota lignite provided by Great River Energy. This had been crushed at the mine to a 6.35 mm (¼") top size and shipped to the Energy Research Center in barrels. Typical size distribution is shown in Figure 7. Average particle size, computed as

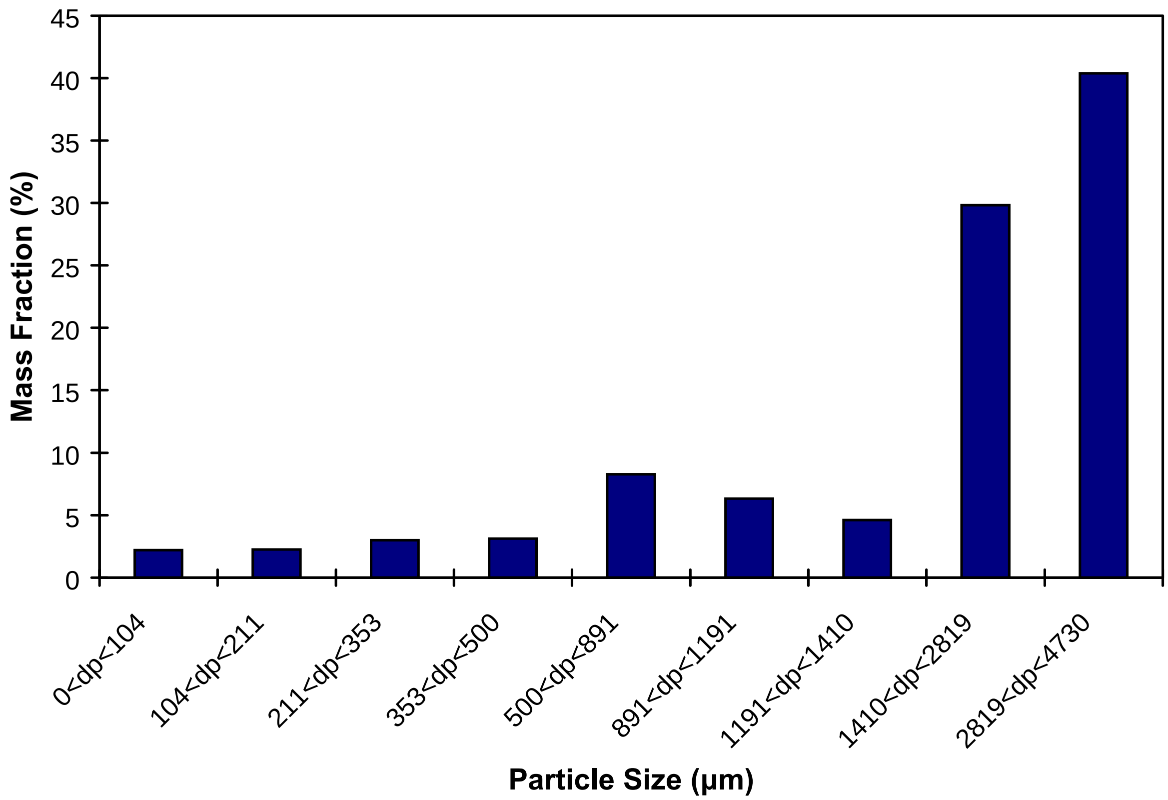

Figure 7: Size Distribution of the Coal

$$\bar{d}_p = \frac{1}{\sum \frac{x_i}{dp_i}}$$

where

x_i = mass fraction in size range i

dp_i = average particle size in size range i

$\bar{d}_p$ = average particle size for entire sample.

was 510 µm for the first group of tests and 655 µm for the second test series. All the tests were performed with a settled bed depth of 0.39 m.

The as received moisture content varied slightly from sample-to-sample, usually ranging from 35 to 38% (expressed as mass of moisture/mass of as-received fuel) and from 54 to 58% (expressed as mass of moisture/mass dry fuel).

During the first minute or two of each test, fines were elutriated from the bed. The drying rate, $\dot{\Gamma}\left(\frac{\text{kg } H_2O}{\text{kg dry coal} \times \text{min}}\right)$, presented here is based on the dry coal which remained in the bed after elutriation had occurred and after coal samples had been removed for analysis.

Figure 8 shows the coal moisture content $\Gamma\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$ as a function of drying time for 6 different drying tests. The corresponding velocities and temperatures are shown in Table 2. These show characteristic drying behavior, with constant rate drying (constant slope) followed by a reduced rate of drying. Note that at the beginning of each test $\Gamma \approx 55$ to 58 percent. Γ can related to the moisture content Y obtained from a proximate analysis, where Y has the units $\left(\frac{\text{kg } H_2O}{\text{kg wet coal}}\right)$. Figure 9 gives the relation between Y and Γ.

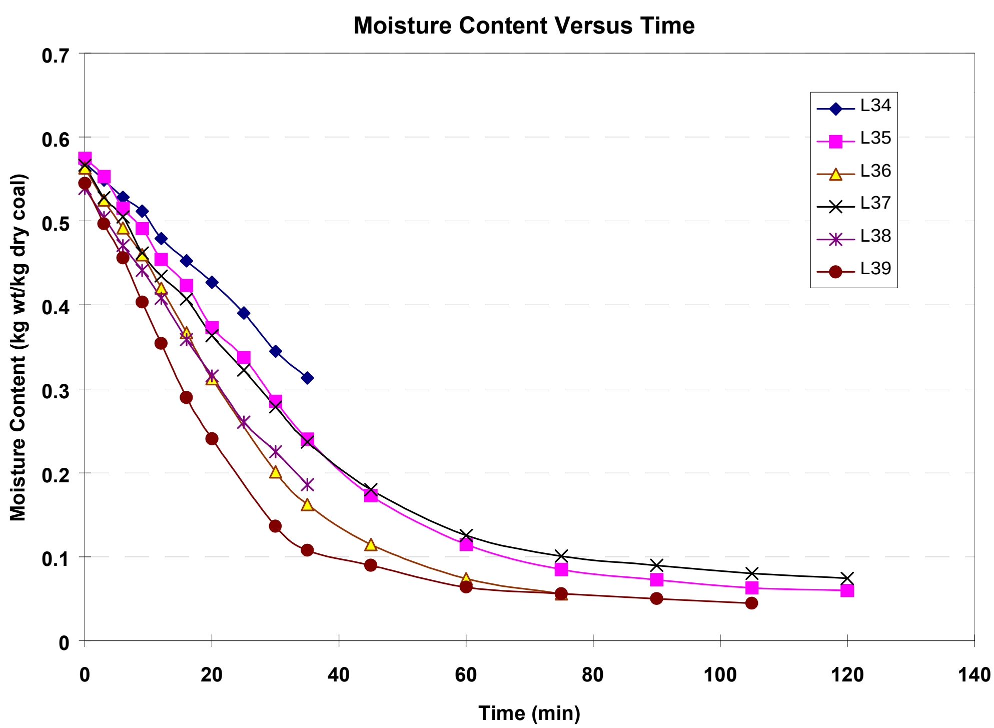

Figure 8: Moisture Content Versus Time

Table 2

Drying Conditions

Test #	Test Condition	$T_{a,in}$	h_o	U_o	Q_{ave}	Q_{ave}/V_{bed}	Drying Rate	Relative Air Humidity	$Q/M_{wet\ coal}$	$M_{wet\ coal}$	ω_{out}	ω_{in}	T_b (^oC)
		(C)	(m)	(m/s)	(W)	(W/m^3)	(kg/kg*min)	at Exit @ 30 min (%)	q/m	(Kg)			
15	2D, Ta,in = 43 C	43	0.39	0.60	319	44441	0.0021	98	65.68	3.80	0.0182		24
16	2D, Ta,in = 43 C	43	0.39	0.80	542	75508	0.0040	87	108.61	4.04	0.0177	0.0060	26
17	2D, Ta,in = 43 C	43	0.39	1.65	529	73697	0.0098	60	116.55	3.45	0.0143	0.0060	27
18	2D, Ta,in = 43 C	43	0.39	1.02	647	90136	0.0077	62	137.79	3.67	0.0176	0.0023	26
19	2D, Ta,in = 43 C	43	0.39	1.22	661	92086	0.0081	71	132.09	3.89	0.0159	0.0023	26
20	2D, Ta,in = 43 C	43	0.39	0.22	155	21594		88			0.0197	0.0032	23
21	2D, Ta,in = 43 C	43	0.39	0.37	163	22708		87			0.0172	0.0032	24
22	2D, Ta,in = 43 C	43	0.39	0.62	524	73000		72			0.0166	0.0032	27
23	N/A	43	0.39	1.02	0	0	0.0048	81	NA		0.0122	0.0050	19
24	N/A	43	0.39	1.26	0	0	0.0058	76	NA		0.0121	0.0062	19
25	N/A	43	0.39	1.53	0	0	0.0067	73	NA		0.0120	0.0050	21
26	2D, Ta,in = 43 C	43	0.39	1.02	563	78434	0.0069	75	114.84	4.07	0.0159	0.0066	23
27	2D, Ta,in = 43 C	43	0.39	1.26	542	75508	0.0072	72	99.66	4.11	0.0159	0.0066	25
28	2D, Ta,in = 43 C	43	0.39	1.51	561	78155	0.0085	64	109.11	3.94	0.0147	0.0049	24
29	3D, Ta,in = 43 C	43	0.39	1.02	310	43187	0.0060	78	62.53	4.16	0.0151	0.0049	22
30	3D, Ta,in = 43 C	43	0.39	1.26	310	43187	0.0070	74	66.94	3.90	0.0140	0.0041	22
31	3D, Ta,in = 43 C	43	0.39	1.56	290	40401	0.0079	70	60.43	3.94	0.0137	0.0041	23
32	2D, Ta,in = 43 C	43	0.39	1.02	539	75090	0.0070	75	122.42	4.03	0.0166	0.0056	23
33	2D, Ta,in = 43 C	43	0.39	1.56	509	70911	0.0085	68	113.48	4.00	0.0148	0.0056	23
34	2D, Ta,in = 43 C	43	0.39	1.14	561	78155	0.0075	72	128.88	3.97	0.0161	0.0082	24
35	2D, Ta,in = 54 C	54	0.39	1.15	792	110337	0.0098	62	190.00	3.83	0.0196	0.0052	36
36	2D, Ta,in = 66 C	66	0.39	1.15	961	133881	0.0127	59	227.13	3.77	0.0245	0.0036	38
37	2D, Ta,in = 43 C	43	0.39	1.56	532	74115	0.0092	64	143.10	3.39	0.0141	0.0037	29
38	2D, Ta,in = 54 C	54	0.39	1.54	727	101281	0.0111	51	170.03	3.80	0.0189	0.0082	29
39	2D, Ta,in = 66 C	66	0.39	1.58	591	82334	0.0155	26	152.10	3.53	0.0204	0.0046	43

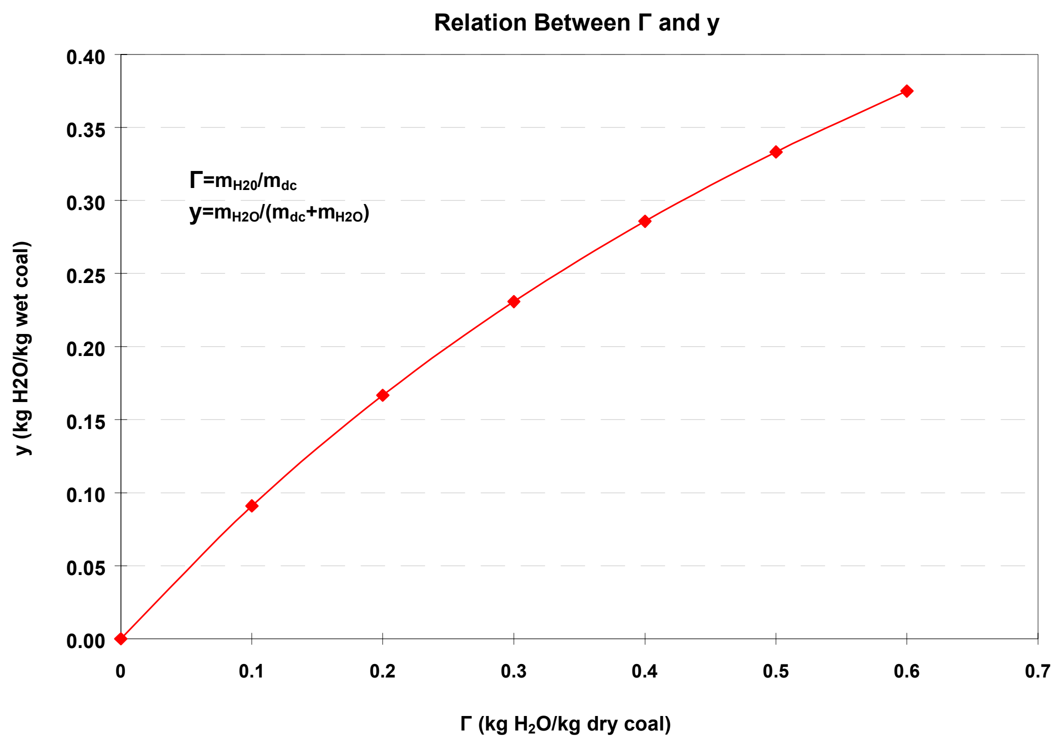

Figure 9: Relationship Between Γ and y

The superficial air velocities U_0 are defined as $\dfrac{\dot{m}_{air}}{\rho A}$

where A = Bed Cross Sectional Area Without Tube Bundle

ρ = Density of Air at Standard T & P

Repeatability

Figure 10 shows three data sets for the same temperature conditions [$T_{air\ in}$ = 110°F, $T_{TUBE\ WALL}$ = 110°F] and U_0 = 1.02 to 1.6 m/s. These replicate data indicate the degree of repeatability of the drying tests when the coal feed has a fixed size distribution.

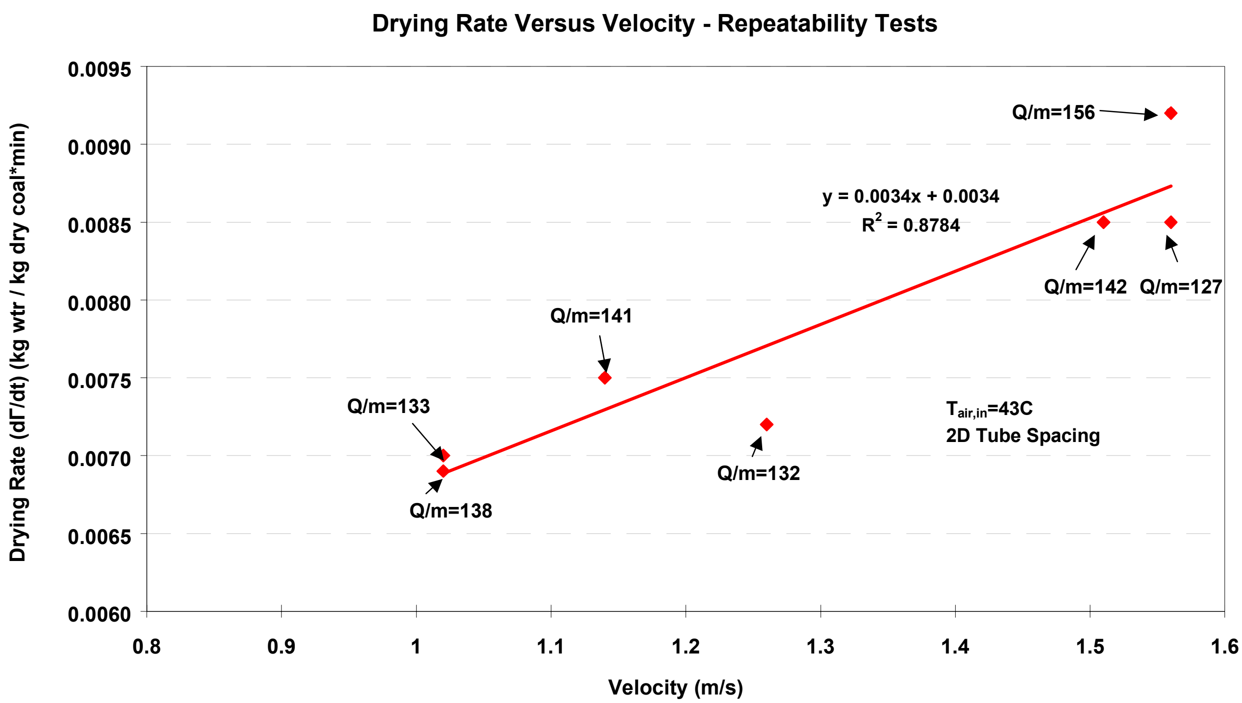

Figure 10: Drying Rate Versus Velocity – Repeatability Tests

Data Consistency

One way to assess the consistency of the data is to compare the measured values of moisture removed from the coal to the moisture added to the air. The mass balance for H_2O requires

$$m_{DC}\frac{d\Gamma}{dt} = -\dot{m}_{air}\left[\omega_{OUT} - \omega_{IN}\right]$$

where

ω = Specific Humidity of Air

Γ = Moisture Content of Coal $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$

$\dot{m}_{air}$ = Mass Flow Rate of Dry Air

m_{DC} = Mass of Dry Coal

$\dot{\Gamma} = \frac{d\Gamma}{dt}$ = drying rate

Figure 11 compares $\dot{\Gamma}$ based on coal moisture measurements, to $\dot{\Gamma}$ based on air moisture measurements. The 45° line indicates perfect agreement. The data show a small bias which ranges from approximately 9 percent at low drying rates to 3 percent at high drying rates.

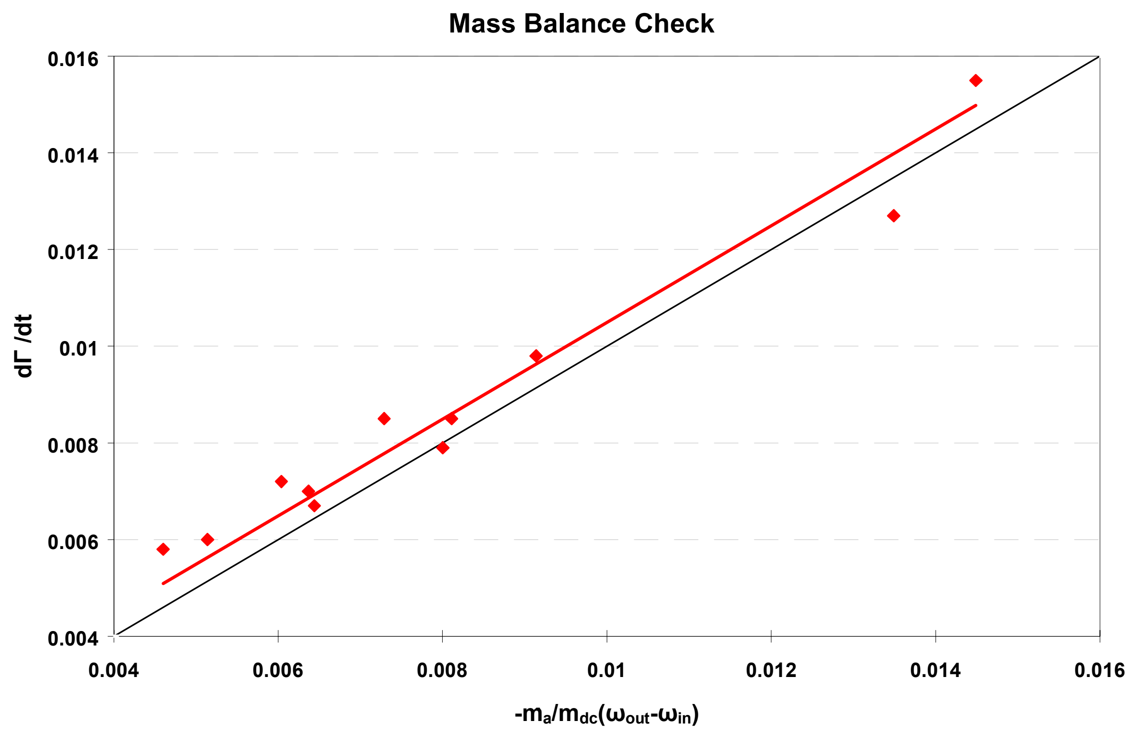

Figure 11: Mass Balance Check

Effects of Drying Temperature and In-Bed Heat Flux

Figure 12 shows the effect of inlet air and tube wall temperature on drying rate. Figure 13 shows the effect of in-bed heat transfer for fixed inlet air and tube wall temperatures. Drying rate increased almost two-fold as T (air and tube wall) increased from 110° to 150°F. However, in-bed heat transfer had a smaller effect on $\dot{\Gamma}$ as the in-bed tube spacing went from 2D to ∞ (or $\frac{\dot{Q}}{m} = 140$ to $\frac{\dot{Q}}{m} = 0$) at constant drying temperature. All the data are compared in Figure 14.

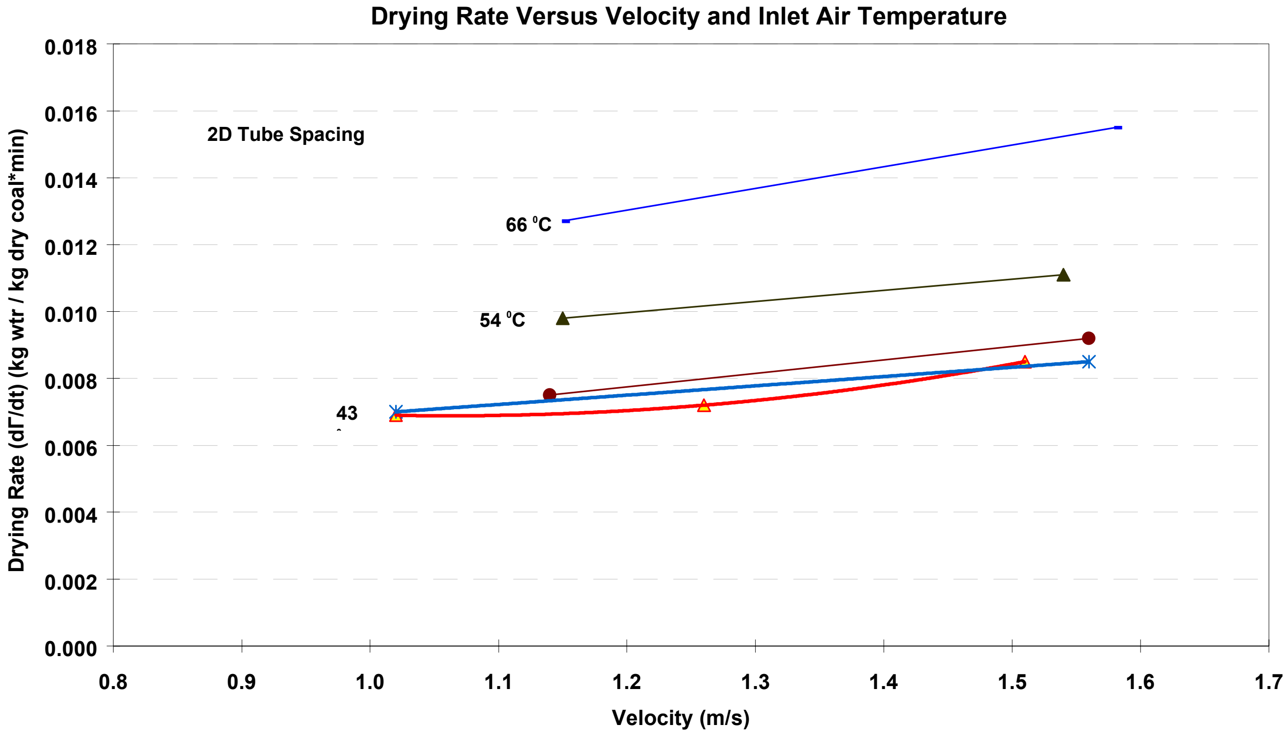

Figure 12: Drying Rate Versus Velocity and Inlet Air Temperature

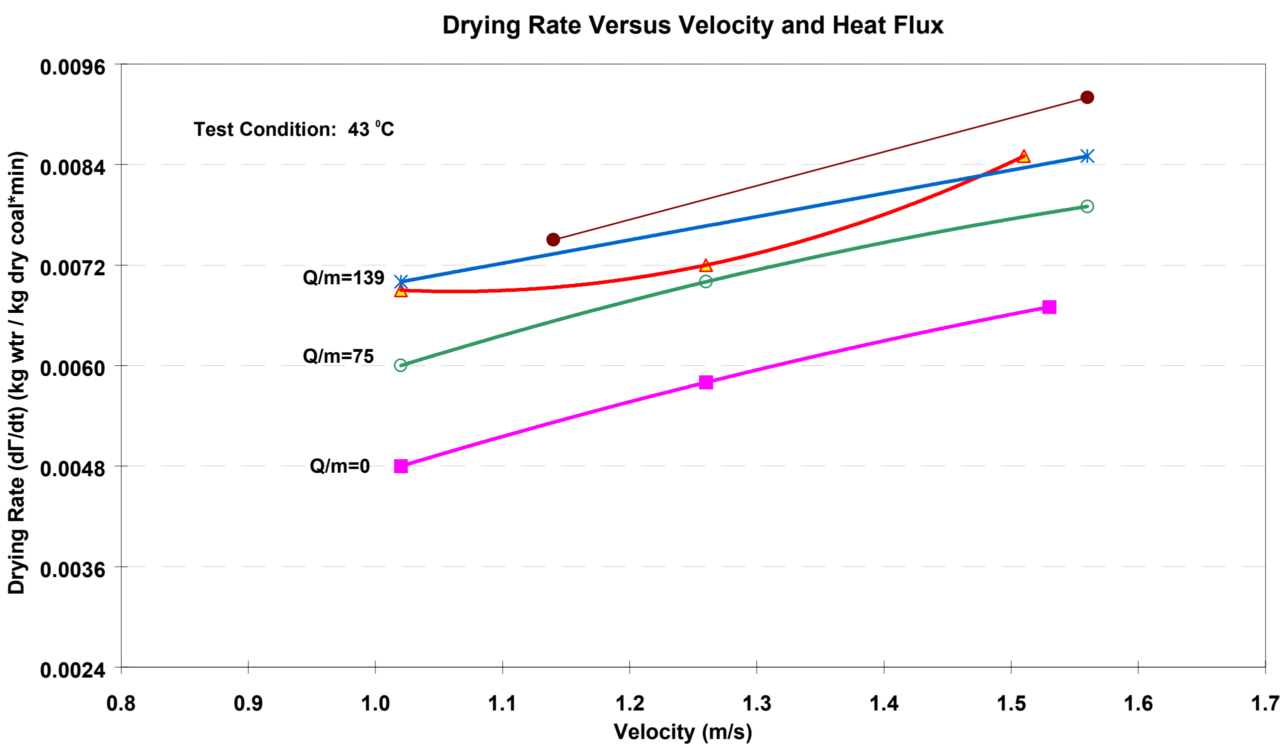

Figure 13: Drying Rate Versus Velocity and Heat Flux

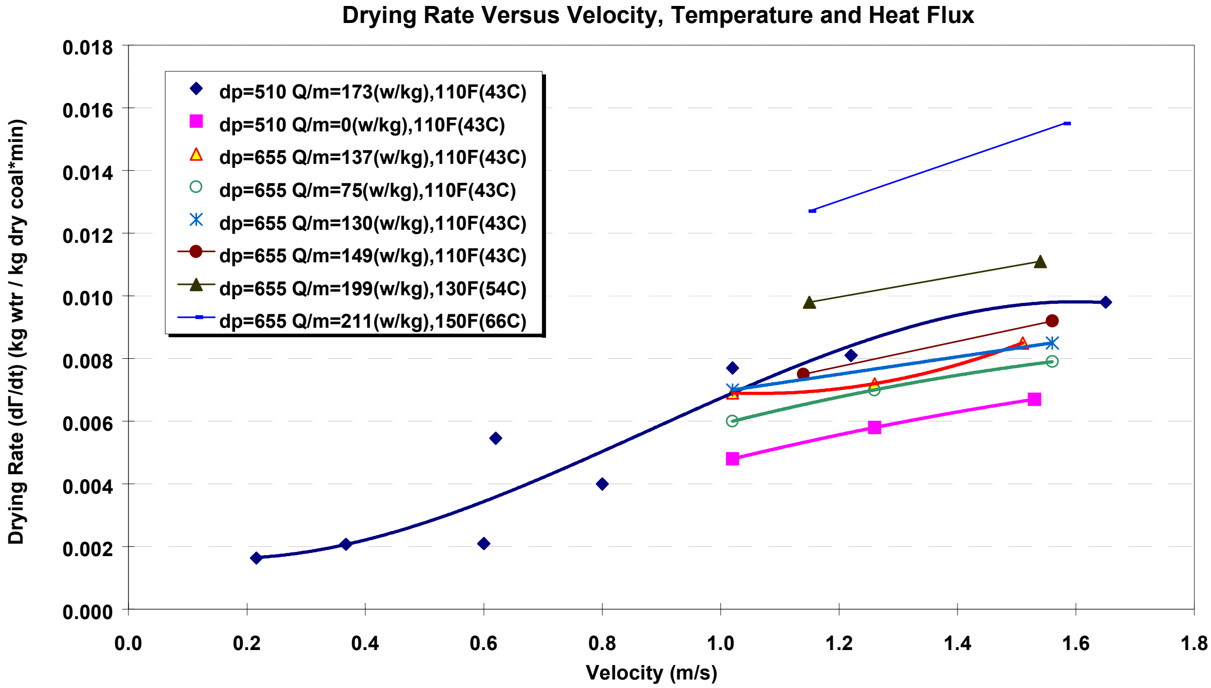

Figure 14: Drying Rate Versus Velocity, Temperature and Heat Flux

Figures 15 to 18 show more details of the drying process for one set of operating conditions (Test 34). The drying curve is shown in Figure 15. Exit air and bed temperatures (Figures 16 and 17), which were roughly equal to one another, increased by about 2°C over the first 30 minutes of drying. The specific humidity of the exit air decreased slightly as the air temperature increased (Figure 18).

The effects of drying temperature and velocity on $\dot{\Gamma}$, bed temperature and exit specific humidity are shown in Figures 19 to 21. In-bed heat flux had only a small effect on bed temperature for fixed drying temperature as seen by Figure 22.

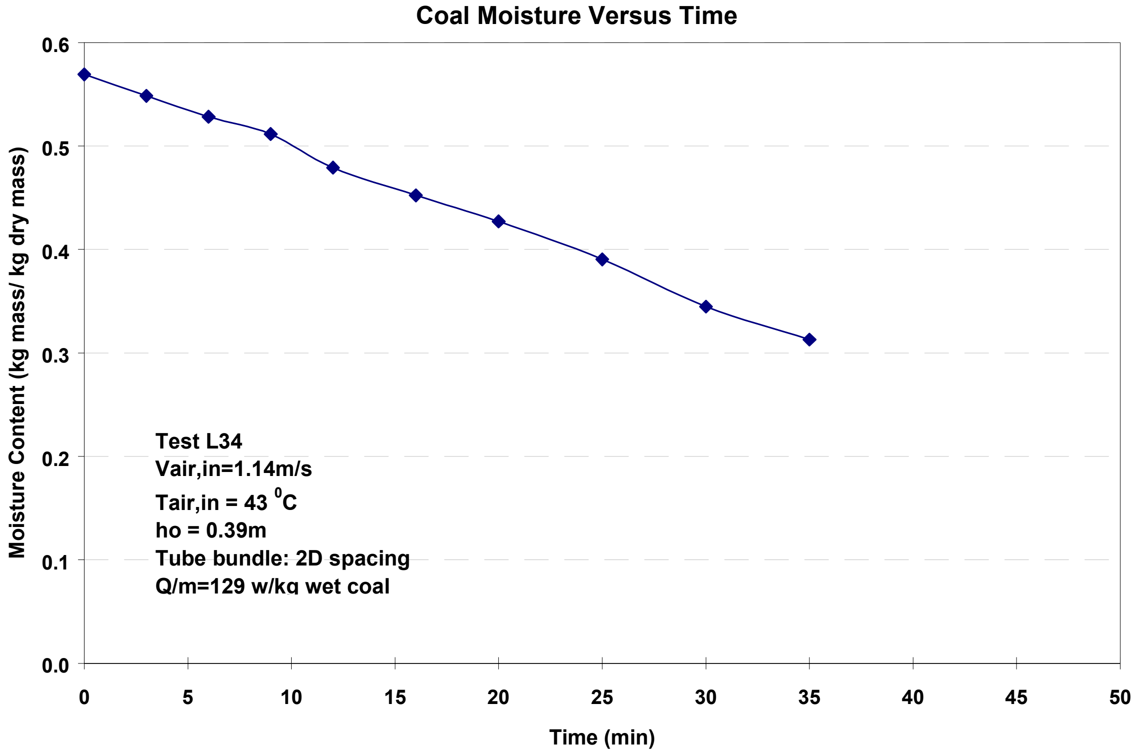

Figure 15: Coal Moisture Versus Time

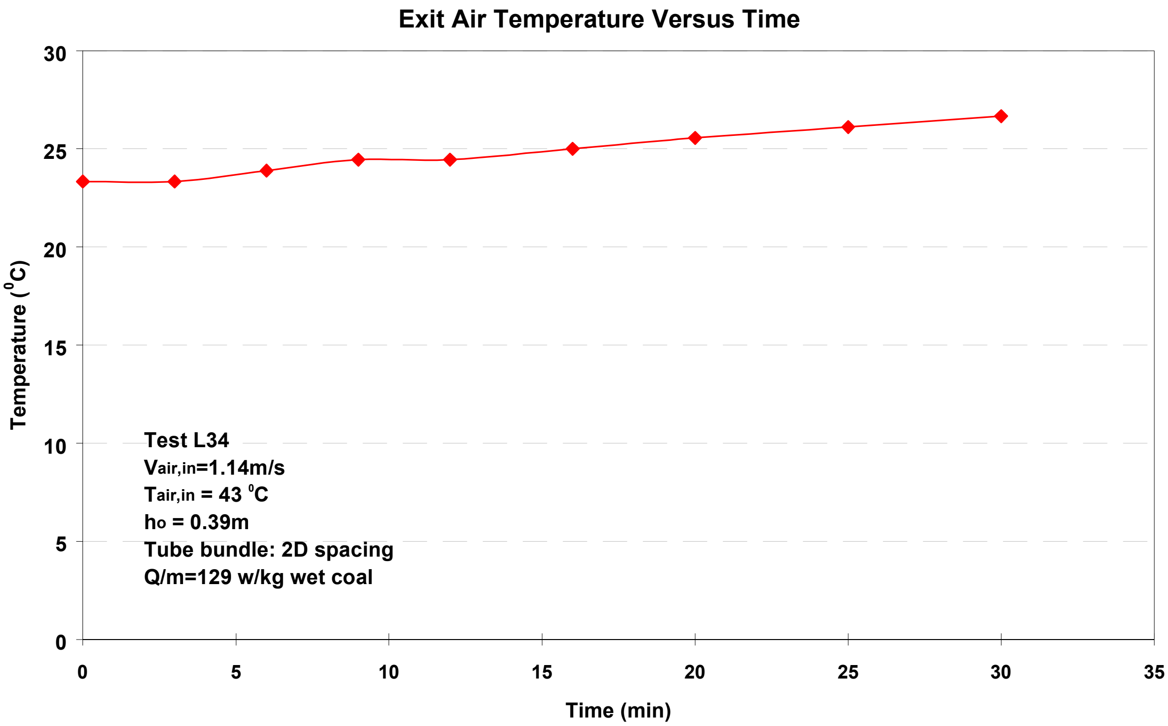

Figure 16: Exit Air Temperature Versus Time

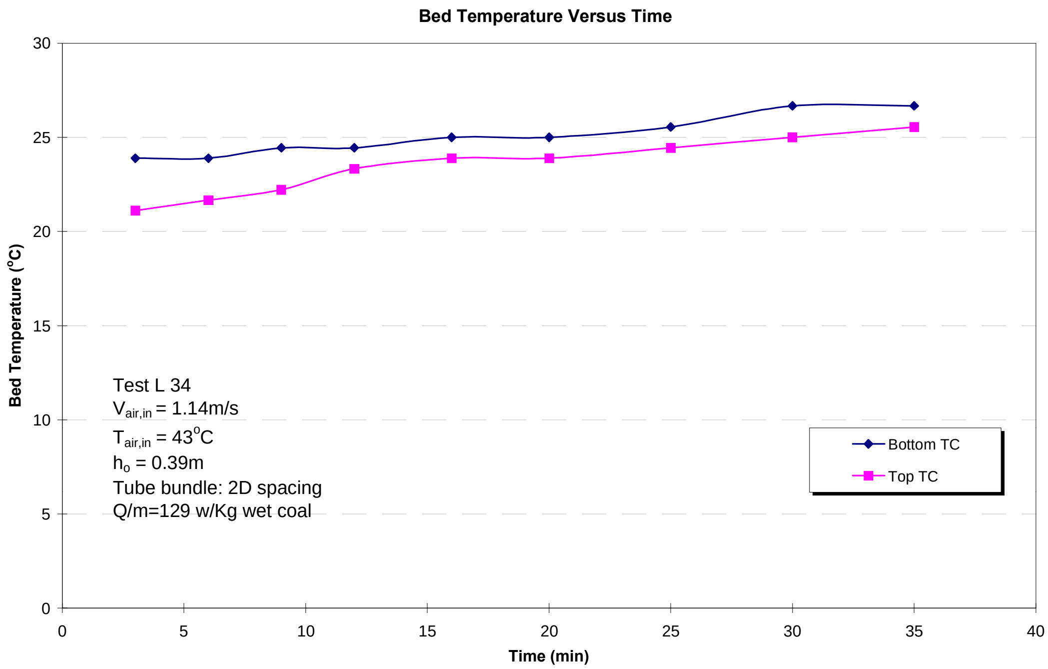

Figure 17: Bed Temperature Versus Time

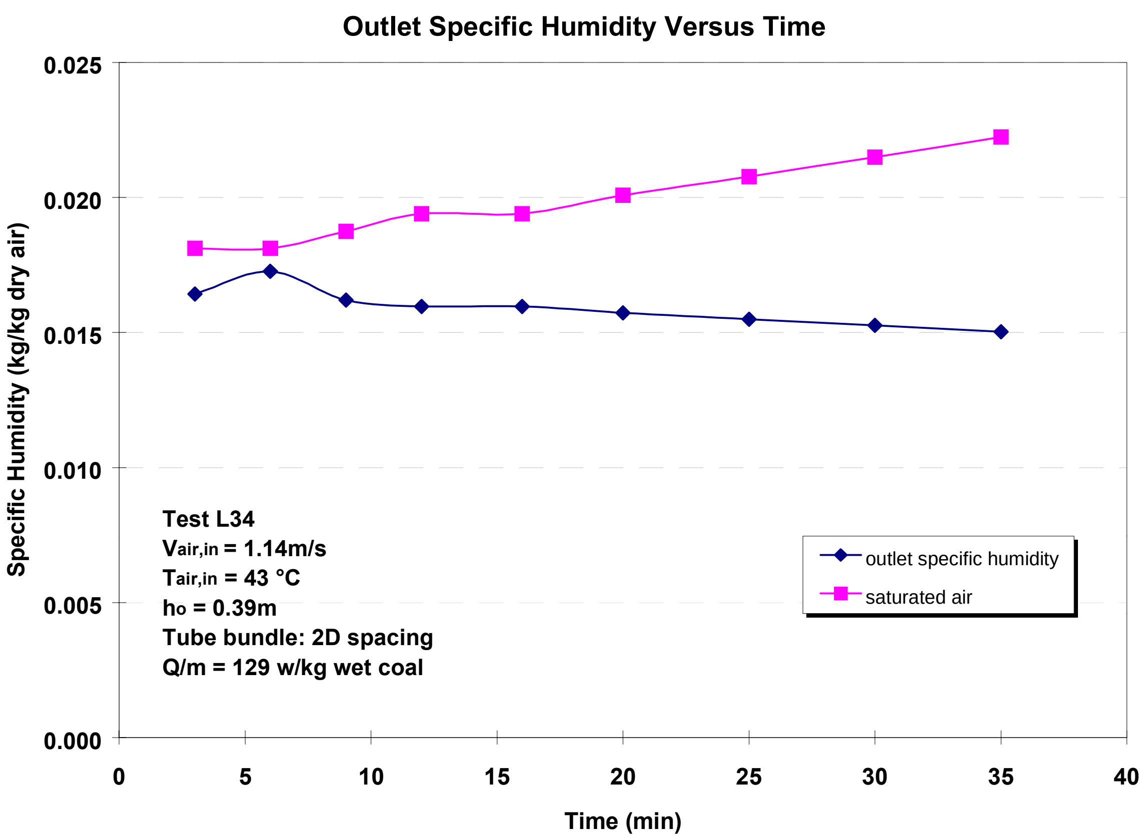

Figure 18: Outlet Specific Humidity Versus Time

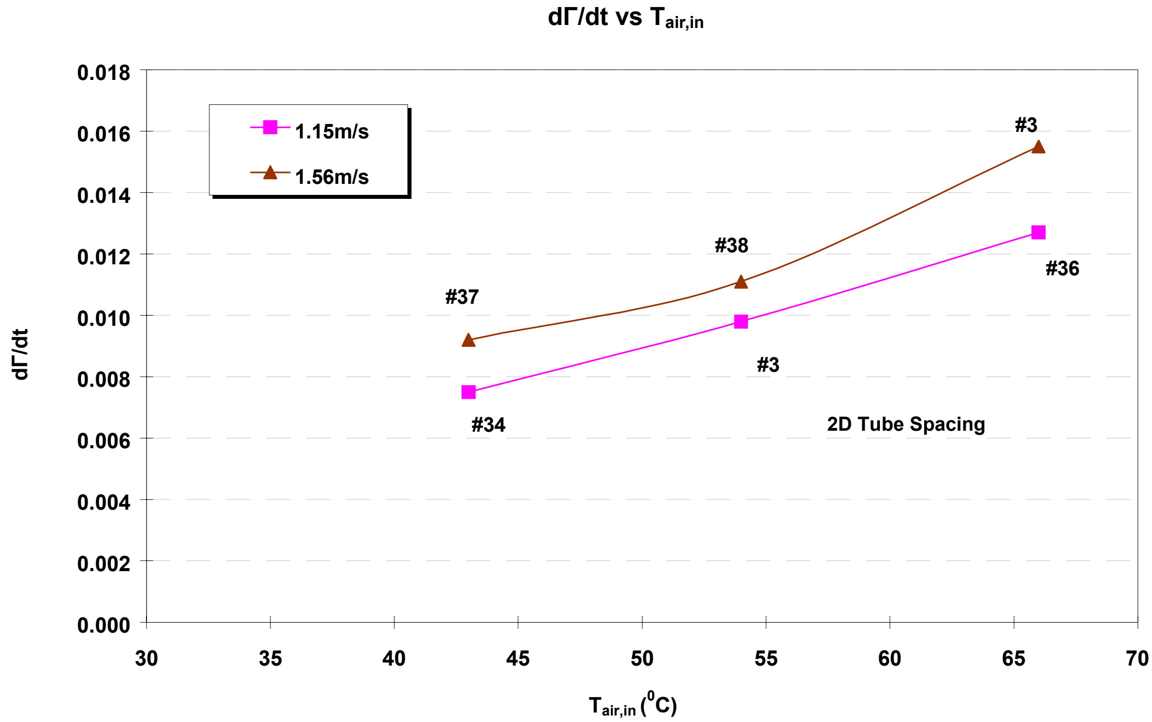

Figure 19: $d\Gamma/dt$ Versus $T_{air,in}$

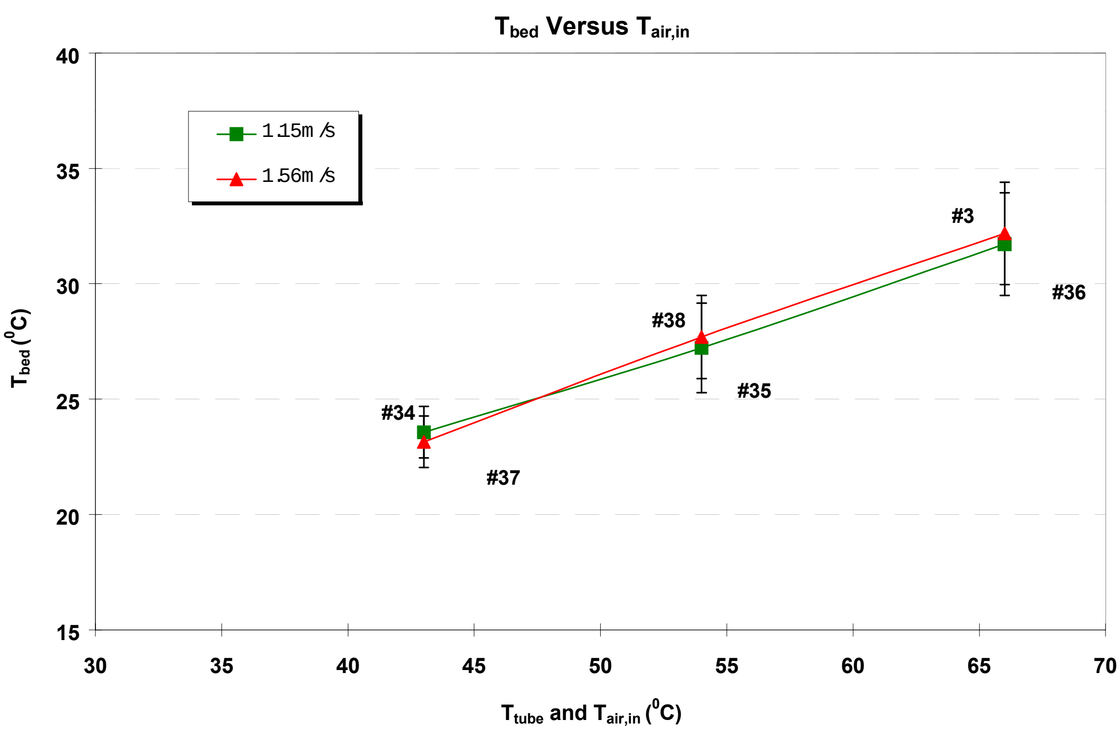

Figure 20: T_{bed} Versus $T_{air,in}$

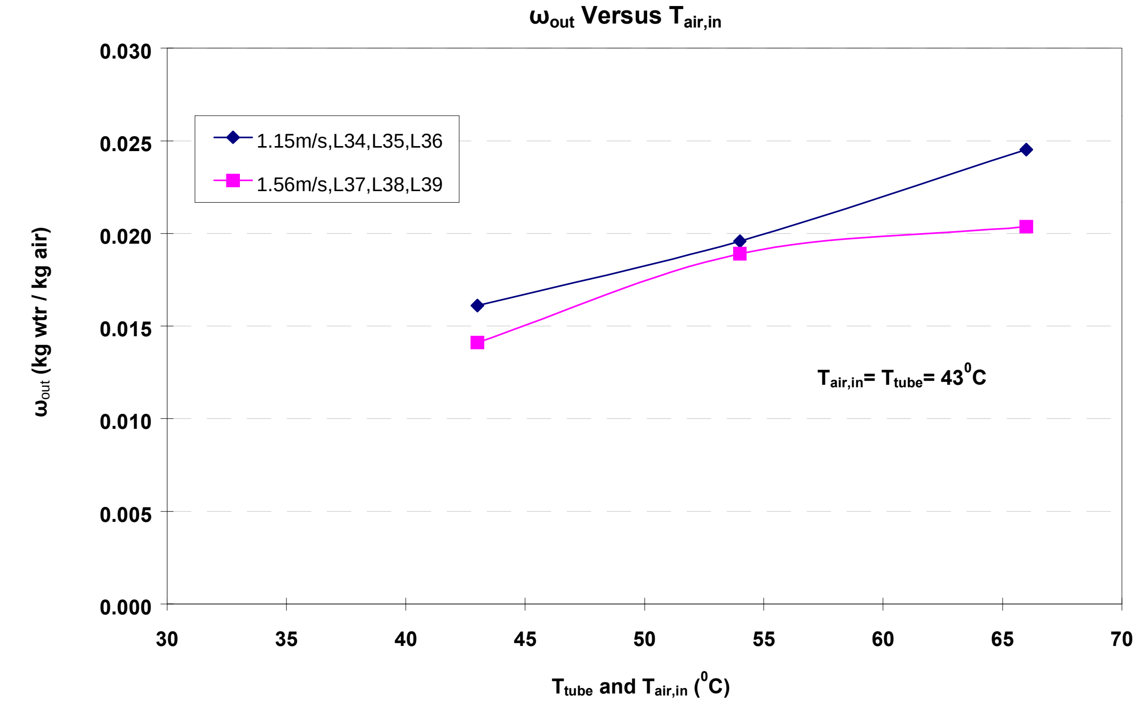

Figure 21: ω_{out} Versus $T_{air,in}$

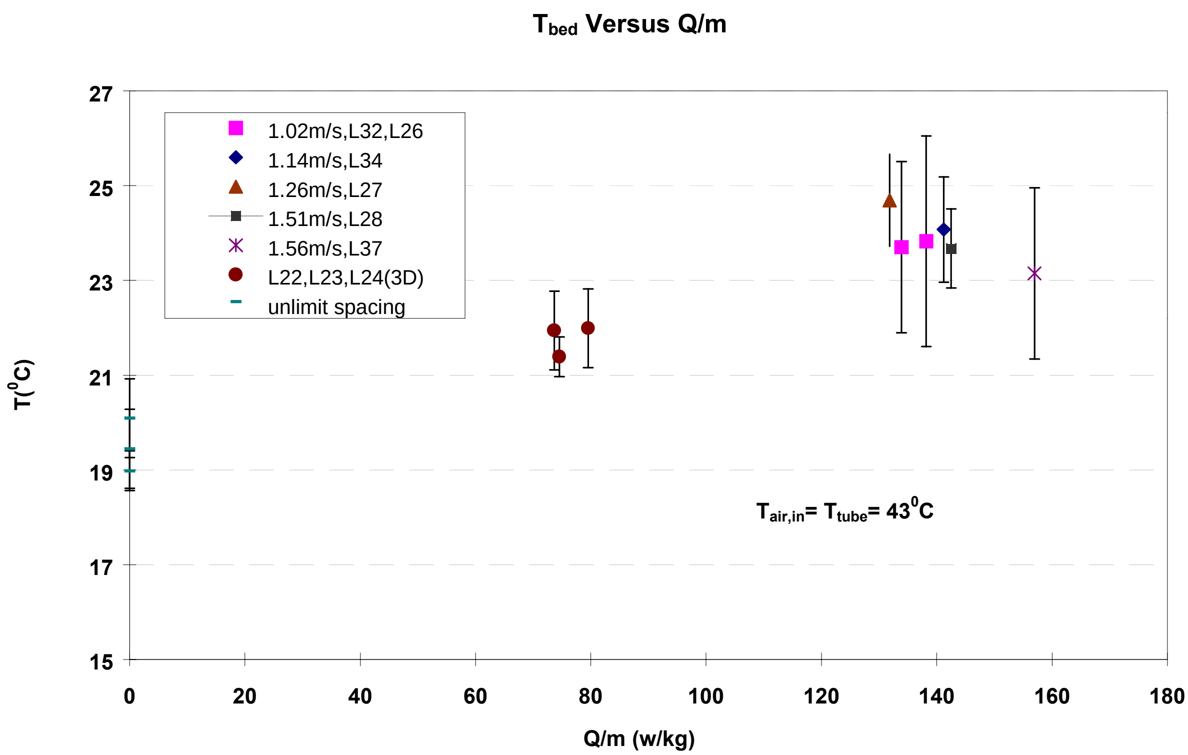

Figure 22: T_{bed} Versus Q/m

DRYING MODELS

The task on developing models for predicting rate of drying was initiated during this last quarter. We expect to have some modeling results to report in the next quarterly report.

CONCLUSIONS

Much of the effort during the first year of the project focuses on the effects of dryer process conditions on drying rate. Having this information is key to being able to design dryers for this application, to estimate the costs of the drying system equipment and its operating costs, and to estimate the impacts of drying on cost of energy. Drying rate depends on superficial air velocity, bed depth, particle size distribution, drying temperature, heat flux from in-bed heat exchanger to bed material, and specific humidity of inlet air.

The experiments carried out during the second quarter were performed with 6.35 mm (¼") top size lignite. Batch experiments on drying rate were carried out as a function of superficial gas velocity, inlet air and tube wall temperature, and in-bed heat flux. In all cases, the initial drying rate was constant and then it decreased as drying progressed. The rate of drying during the constant rate period increased with velocity, temperature, and in-bed heat flux, and quantitative results on these relationships are contained in this report.

The experiments during the next quarter will measure the effects of particle feed size, bed depth and inlet air humidity on rate of drying of lignite. Experiments will also be initiated on drying of PRB coal.

Finally, work will continue on models for predicting rate of drying.

REFERENCES

1. Bullinger, C., M. Ness, N. Sarunac, E. Levy, "Coal Drying Improves Performance and Reduces Emissions," Presented at the 27th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, March 4-7, 2002.

NOMENCLATURE

d_p	Particle Size
h_o	Settled Bed Depth
$\dot{m}_{air}$	Air Flow Rate
$M_{wet\ coal}$	Mass of Wet Coal
M_{DC}	Mass of Dry Coal
Q_{ave}	Average Heat Flux to Bed
$T_{a,\ in}$	Air Inlet Temperature
T_b	Bed Temperature
U_o	Superficial Air Velocity
V_{Bed}	Bed Volume
Y	Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg } H_2O + \text{kg dry coal}}\right)$
Γ	Coal Moisture $\left(\frac{\text{kg } H_2O}{\text{kg dry coal}}\right)$
$\dot{\Gamma}$	Drying Rate = $\frac{d\Gamma}{dt}$
ω	Specific Humidity of Air